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ISRO'S SOLID ROCKET MOTORS†

R. NAGAPPA, M. R. KURUP and A. E. MUTHUNAYAGAM
Indian Space Research Organization, Vikram Sarabhai Space Centre, Trivandrum 695022, India

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Abstract—Solid rocket motors have been the mainstay of ISRO's sounding rockets and the first generation satellite launch vehicles. For the new launch vehicle under development also, the solid rocket motors contribute significantly to the vehicle's total propulsive power. The rocket motors in use and under development have been developed for a variety of applications and range in size from 30 mm dia employing 450 g of solid propellant—employed for providing a spin to the apogee motors—to the giant 2.8 m dia motor employing nearly 130 tonnes of solid propellant. The initial development, undertaken in 1967 was of small calibre motor of 75 mm dia using a double base charge. The development was essentially to understand the technological elements. Extruded aluminium tubes were used as a rocket motor casing. The fore and aft closures were machined from aluminium rods. The grain was a seven-pointed star with an enlargement of the port at the aft end and was charged into the chamber using a polyester resin system. The nozzle was a metallic heat sink type with graphite throat insert. The motor was ignited with a black powder charge and fired for 2.0 s. Subsequent to this, further developmental activities were undertaken using PVC plastisol based propellants. A class of sounding rockets ranging from 125 to 560 mm calibre were realized. These rocket motors employed improved designs and had delivered I_{sp} ranging from 2060 to 2256 Ns/kg. Case bonding could not be adopted due to the higher cure temperatures of the plastisol propellants but improvements were made in the grain charging techniques and in the design of the igniters and the nozzle. Ablative nozzles based on asbestos phenolic and silica phenolic with graphite inserts were used. For the larger calibre rocket motors, the I_{sp} could be improved by metallic additives. In the early 1970s designs were evolved for larger and more efficient motors. A series of 4 motors for the country's first satellite launch vehicle SLV-3 were developed. The first and second stages of 1 and 0.8 m dia respectively used low carbon steel casing and PBAN propellant. The first stage used segmented construction with a total propellant weight of 8600 kg. The second stage employed about 3 tonnes of the same propellant. The third and fourth stages were of GFRP construction and employed respectively 1100 and 275 kg of CTPB type propellants. Nozzle expansion ratios upto 30 were employed and delivered vacuum I_{sp} of 2766 Ns/kg realized. The fourth stage motor was subsequently used as the apogee motor for orbit injection of India's first geosynchronous satellite—APPLE. All these motors have been flight proven a number of times. Further design improvements have been incorporated and these motors continue to be in use. Starting in 1984 design for a large booster was undertaken. This booster employs a nominal propellant weight of 125 tonne in a 2.8 m dia casing. The motor is expected to be qualified for flight test in 1989. Side by side a high performance motor housing nearly 7 tonnes of propellant in composite casing of 2 m dia and having flex nozzle control system is also under development for upper stage application. Details of the development of the motors, their leading specifications and performance are described.

1. INTRODUCTION

Solid rockets have played an important role, since the beginning of modern rocketry in India in 1963, to propel payloads to their destined apogees and orbits. The foundation for rocketry in India was established in November 1963 with the launching of a two-staged NASA supplied Nike-Apache sounding rocket from Thumba near Trivandrum. Indigenous development of rockets was not far behind with the initial effort aimed at learning the technology. Small calibre rockets with all elements of solid rocket systems—motor case, propellant, insulation, igniter, nozzle, charging and testing techniques—were developed and taken through a series of ground tests, culminating in a successful flight test in 1967. Subsequent to this, development of larger calibre rockets for sounding rocket applications were undertaken. Design and manufacturing techniques of these were perfected and the rockets were made operational following ground and flight qualification tests. Subsequent to this, development of larger and high performance rocket motors for India's first satellite launch vehicle—SLV-3 was undertaken and successfully flown on four missions. Improvements were carried out in the stage motors and these improved versions are being used in the next generation satellite launch vehicle—the ASLV. Currently under development are 2.8 m dia motors containing nearly 125 tonnes of solid propellant and a 2 m dia motor containing 7 tonnes of

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propellant for the polar satellite launch vehicle. Various developmental aspects and leading particulars of these motors are described in the following sections.

2. ROCKETS FOR TECHNOLOGY DEVELOPMENT

A 75 mm dia rocket was taken up for initial propulsion technology development demonstration. The diameter was chosen to use off the shelf items to the extent possible and minimize development time. Double base, free standing grains of 67 mm dia were already under manufacture in the country. A quick survey showed that extruded aluminium alloy tubes conforming B 51 SWP of 75 mm dia and 2 mm wall thickness were also readily available. The fore and aft closures were made from aluminium alloy rods and were threaded on to the chamber. A basket igniter of black powder and SR 371 mixture was used for initiating the combustion. For the nozzle, a metallic heat sink design was adopted with polycrystalline graphite for throat insert. The propellant grain was charged into the aluminium chamber and bonded in place with a polyester resin system.

The motor was ground tested and subsequently flight tested with a suitably designed fin aft body. The motor had a burn time of little over 2 s, developing a thrust of about 5 kN. The development of the motor gave useful inputs towards:

(a) design and performance,
(b) propellant charging techniques,
(c) test stand design and testing techniques,
(d) flight testing.

Subsequent to this, a programme to develop rocket staging techniques using a booster of nominal diameter of 125 mm was undertaken. The change made in this was the substitution of the base propellant system with a PVC based plastisol system. The delivered I_{sp} of this motor was 2060 Ns/kg as, compared to the double base propellant system used in the RH-75 motor. This propellant had higher energetics resulting in higher combustion temperature. Hence, better insulation techniques had to be employed. The PVC plastisol propellant, because of its cure temperature in the region of 170°C, was not amenable for case bonding technique. The propellant was cast in a PVC restrictor tube, which served as insulator. Both the booster and upper stage motors were of the same diameter and separated in flight by atmospheric drag action. The important inputs derived from this programme were:

(a) improvement in a propellant formulation and processing,
(b) handling and charging of flexible propellant grains,
(c) staging and stage separation techniques.

Features	Type of rocket			
	RH-200	RH-300	RH-300MkII	RH-560
No. of stages	2	1	1	2
Length, m	3.6	4.4	3.8	7.7
Weight at lift off, kg	108	370	504	1350
Payload wt, kg	10	50	60	100
Attitude, km	80	100	160	350
Field of application	Meteorology	Middle atmosphere	Upper middle atmosphere	Ionosphere

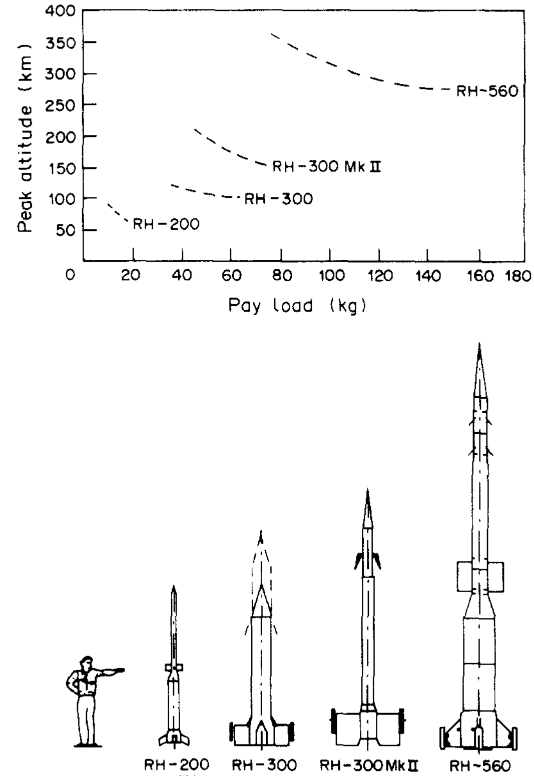


Fig. 1. Operational sounding rockets.

3. SOUNDING ROCKETS

Atmospheric sounding studies have been going on since 1963 using the Nike-Apache and the Centaure II B rockets. In the late sixties, it was decided to develop a family of sounding rockets capable of exploring the D to F regions. The rockets ranged in diameter from 125 to 560 mm and had capabilities of taking payload ranging from 10 to 100 kg to heights ranging from 80 to 350 km.

While most of the rockets developed were of single stage some of the rockets were of the two-stage construction. Figure 1 shows the details of the family of sounding rockets which are being now produced on operation basis. Some aspects of these sounding rocket motors are described below:

3.1. Motor case

Low carbon alloy steels with UTS of 997 MN/m^2 were employed for the main propulsor body, which

was made by rolling and welding of the steel sheets, and the fore and aft closures were designed and fabricated from forgings. Fabrication using a helical welding technique was also developed and successfully employed in the fabrication of the 200 mm dia rocket chamber. In addition, a technique of winding and bonding alloy steel strips over a mandrel to produce propulsor cylinder bodies were also developed. The end closures were adhesively bonded. All the propulsor chambers were used after subjecting to acceptance hydropressure tests.

3.2. *Propellant system*

The initial devlopment for the RH-125 and RH-200 was based on PVC plastisol propellant. The propellant was modified to obtain higher density by metallizing it and used in the larger RH-560 motor. All these grains are of star configuration and cast as free standing grains in PVC restrictor tubes and then separately charged into the rocket chamber.

Side by side the development of a more energetic composite propellant was also undertaken using a lactone terminated polybutadiene binder system. This propellant system had a 86% solids loading yielding a specific gravity of 1.78 and standard I_{sp} of 2370 Ns/kg. This propellant has been used both in the free standing and case bonded versions.

3.3. *Ignition and nozzle system*

The ignition system consisted of powder/pellet charges in canister/perforated PVC tubes depending upon the type of rocket.

The nozzles for all sounding rockets use graphite as throat insert. For thermal protection of the convergent and divergent hardware, asbestos phenolic liners were used. However, for the RH-560 as the exit cone is comparatively large, carbon phenolic was used. Currently, from safety considerations all the asbestos liners have been replaced by high silica.

The performance details of these motors are indicated in Table 1.

4. MOTORS FOR SATELLITE LAUNCH VEHICLE

India's first satellite launch vehicle SLV-3 was designed to inject a payload of 40 kg into a near Earth orbit. The design and development of various components, subsystems and systems of the vehicle were initiated in late 1973 and culminated with the successful launch and injection of the Rohini Satellite on 18 July 1980.

The base line SLV-3 is a four-stage solid propellant vehicle, 22 m tall and having a lift off weight of 16.9 tonnes.

First stage of 1000 mm dia is made of 15 CDV 6 steel and is loaded with 8660 kg PBAN propellant. Its action time is 49 s and average thrust developed is 441 kN. The stage is controlled by secondary thrust vector and movable fin tips.

Second stage of 800 dia is also of 15 CDV 6 steel and has 3150 kg PBAN propellant. Action time is 39.9 s and average thrust developed is 196 kN. The stage is controlled by bipropellant reaction control system.

Third stage of 815 mm dia is made of fibre reinforced plastic and has 1060 kg of HEF-20 propellant. The action time is 45 s and average thrust developed is 64 kN. This stage is controlled by monopropellant reaction control system.

Fourth stage with 657 mm dia is also a fibre reinforced plastic and has 262 kg HEF-20 propellant. The action time is 33 s and the average thrust developed is 21 kN. Fourth stage is spin stabilized.

The stages are interconnected by aluminium alloy

Table 1. Performance of sounding rocket motors

	RH-200	RH-300	RH-300 MK II	RH-560
1. No. of stages	2	1	1	2
2. Diameter (mm)				
Stage 1	207	305	305	560
Stage 2	122			305
3. Motor case material				
Stage 1	15 CDV 6 Steel	15 CDV 6	15 CDV 6	15 CDV 6
Stage 2	B 51 SWP Al alloy			15 CDV 6
4. MEOP (MPa)				
Stage 1	6.37	4.9	5.1	3.92
Stage 2	6.27			4.9
5. Propellant weight (kg)				
Stage 1	44	244	335	707
Stage 2	14			232
6. Action time (s)				
Stage 1	5.9	16.5	22	22.3
Stage 2	3.6			23.0
7. Delivered sea level Specific impulse (Ns/kg)				
Stage 1	2158	2280	2374	2109
Stage 2	2158			1913
8. Apogee (km)/PL (kg) (Degree QE)	89/16.3 (85)	100/50 (82)	160/60 (82)	360/90 (82)

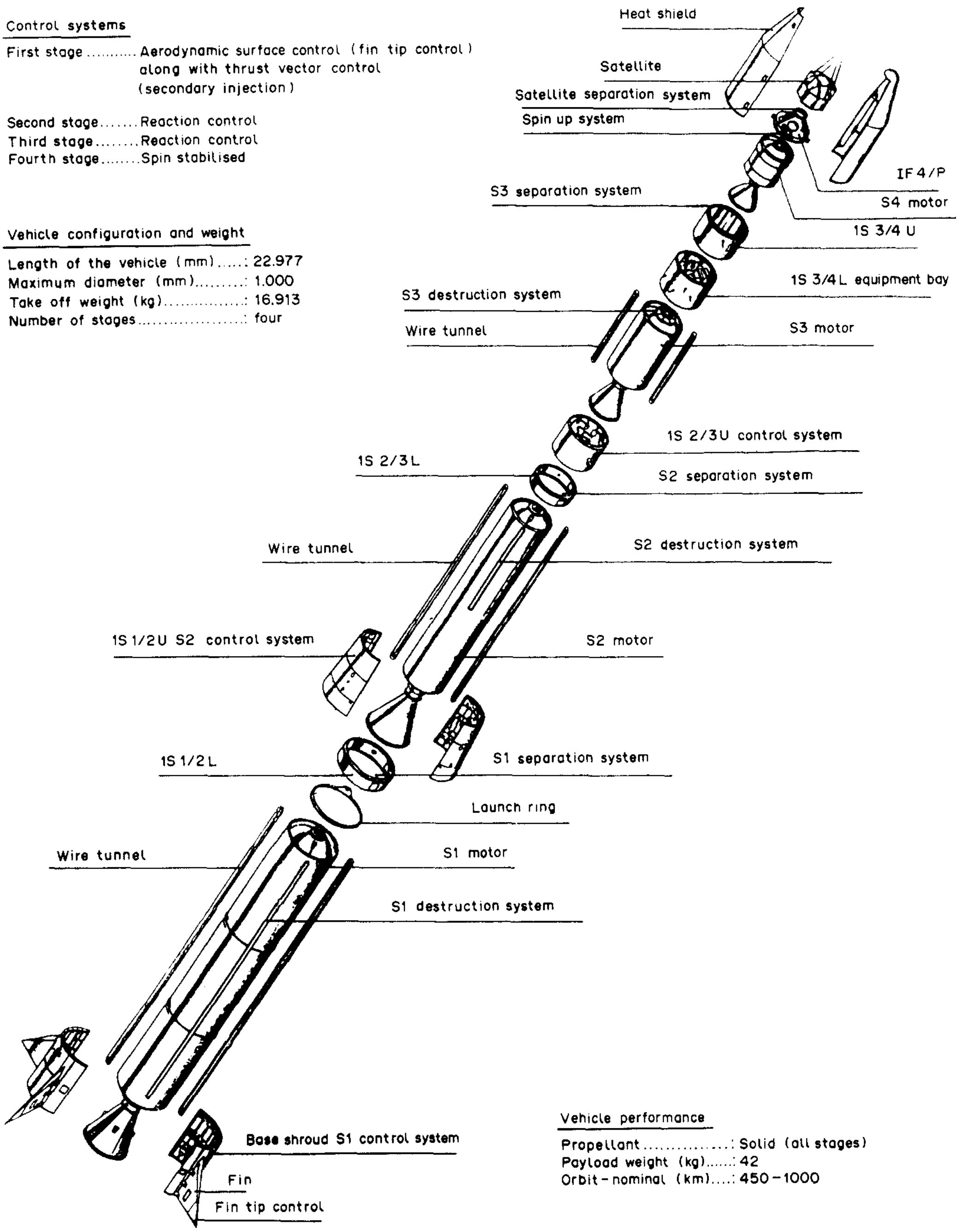


Fig. 2. Exploded view of SLV-3.

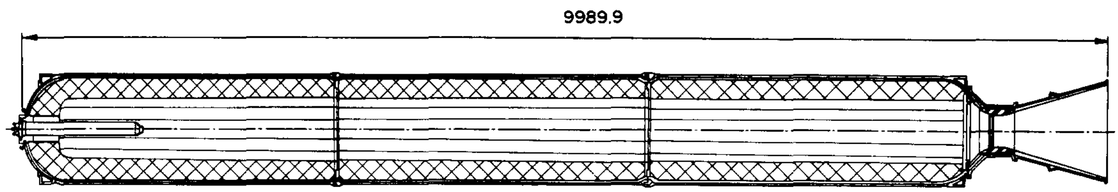
interstages housing instrumentation, control system and separation system. Figure 2 shows the exploded view of the vehicle.

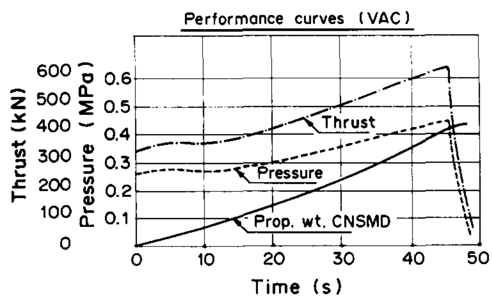
4.1. Lower stage motor

The leading particulars of the two lower stage motors are shown in Figs 3 and 4.

The motor case is made of low C alloy steel with strength properties of 997 MN/m^2 UTS. The case shell is of nominal thickness of 3.5 mm for the first stage and 3 mm for the second stage. The cases are fabricated by conventional rolling and welding techniques. The end closures and the foward and aft skirts are made of 15 CDV 6 forgings and welded on to the shell. Full properties of the material are realized by heat treating to 950°C followed by oil quench. The first stage motor case is made in three segments using a tongue and a groove-type joint held together by means of pins. Segmented joint construction was adopted in order to utilize the existing propellant processing and curing facilities.

The motor employs an 84% solids loading





Design parameters

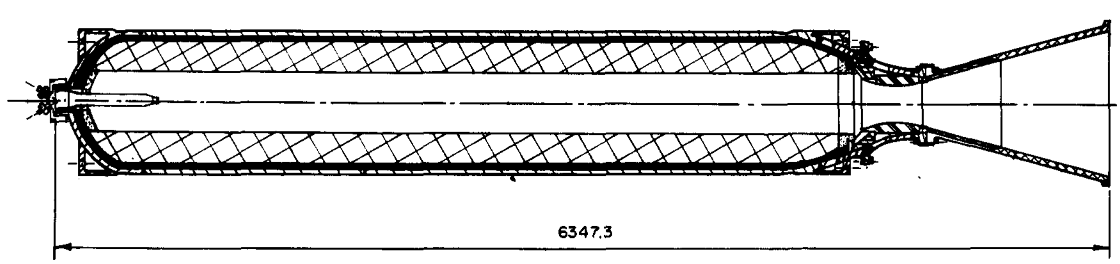
Outside diameter	m	1.0
Propellant weight	t	8.660
Motor mass ratio	–	0.851
Design MEOP	MPa	4.410
Action time VAC Isp	NS/kg	2482
Action time	s	49
Maximum thrust in vacuum	kN	623

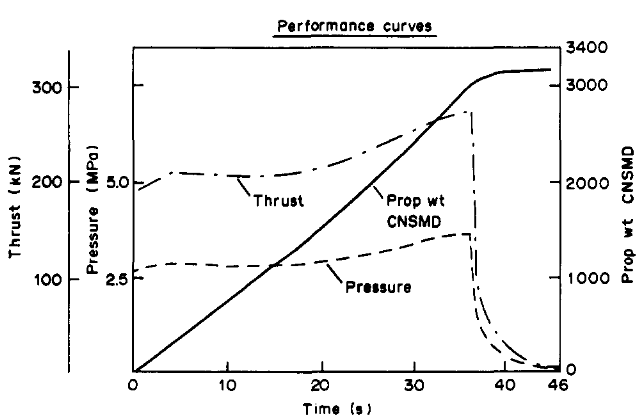
Fig. 3. Stage 1 motor.

AP/AL/PBAN propellant system with a nominal burn rate of 6.5 mm/s at 6.87 MPa and a standard I_{sp} of 2374 Ns/kg. The case was insulated by nitrile-based insulation having a nominal erosion rate of 0.2 mm/s. The propellant grain for both stages is of star configuration having volumetric loading density in excess of 78%. The propellant is case bonded with a liner system between the propellant and the insulation.

Pyrogen igniters having a fast burning propellant composition in FRP chamber are employed for ignition purposes. Ignition occurs within a specified nominal ignition delay of < 200 ms. A pressure closure mounted on the nozzle aids the ignition process. The booster igniter has double the mass flow of the second stage igniter.

The nozzle for the first stage has an area ratio 6.7 while that of the second stage has an area ratio of





Design parameters

Outside diameter	m	0.80
Propellant weight	t	3.15
Motor mass ratio	–	0.843
Design MEOP	MPa	3.826
Action time VAC Isp	Ns/kg	2619
Action time	s	39.9
Maximum thrust in vacuum	kN	267

Fig. 4. Stage 2 motor.

14.2. The construction of the thermal protection system for both nozzles is similar. Carbon-phenolic liner of rosetted construction is used for the convergent part of the nozzle; tape wound carbon and silica phenolic lining is adopted for the fore-end and aft end parts, respectively, of the divergent cone. Graphite backed with an insulation is used for the throat section. The second stage has an FRP structural backup, while the first stage has a metallic structural backup with provision for mounting the SITVC valves.

The motors have been qualified through a series of ground tests before using them for flight purposes. The second stage has been tested in its flight configuration area ratio 14.2 nozzle using a straight duct diffuser system.

4.2. Upper stage motors

These motors operate at MEOP of 4.41 and 2.94 MPa respectively and the motor cases are made of glass fibre reinforced plastic. The case at the fore and aft domes are insulated by pre-moulded nitrile rubber insulation, laid in place prior to the winding of the motor case. All motor cases are acceptance pressure tested to 1.1 times MEOP.

A propellant system functionally similar to CTPB employed is used in the two motors. The radial slotted grain configuration is achieved by a machining process and a form tool.

Ignition is by means of a pyrogen igniter of smaller calibre. Nozzle construction is similar to the booster nozzle already described, except there is no convergent entry section for the nozzle.

Both category of motors have been qualified through environmental condition involving vibration, thermal cycle/soak and longitudinal acceleration. In addition, the apogee motor has been tested under spin conditions and simulated high altitude conditions.

The major details of the motors are described in Figs 5 and 6.

All the above four power plants have given satisfactory performance in the experimental and developmental flights of the SLV-3.

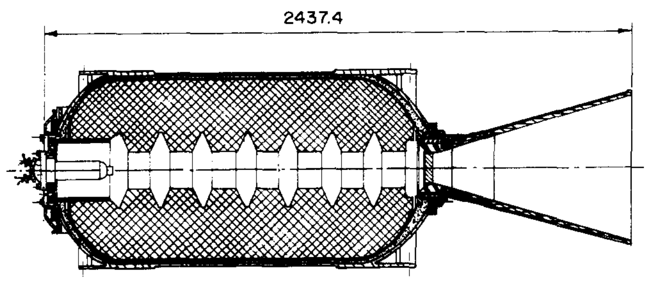
5. MOTOR FOR THE AUGMENTED SATELLITE LAUNCH VEHICLE

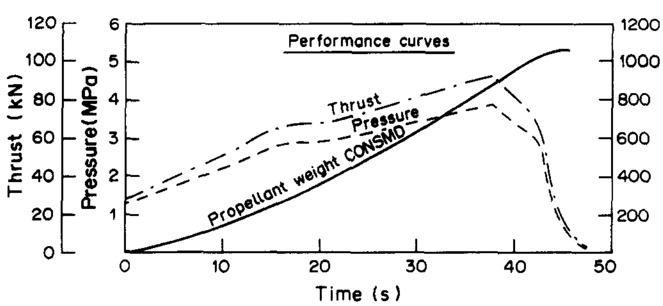
Subsequent to the completion of the SLV missions, augmentating the vehicle to increase the payload capability was conceived by the addition of two of the first stage motors as strap-ons to the SLV-3. The ensuring 5 stage rocket is 23.5 m tall with a lift-off weight of 39 tonnes and can inject 150 kg class of payload in a nominal 400 km orbit.

Besides the addition of the strap-ons, improvements were effected in the propellant system of the first and second stages and in the casing of the fourth stage motor. These are described below:

5.1. Strap-on motors

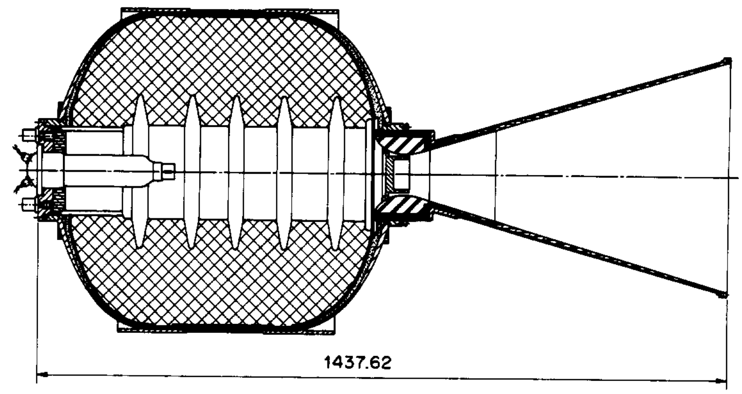
The nozzles were redesigned to obtain a fixed 9° cant. To obtain reproducible and minimal dispersion in the strap-on motors, the mixed propellant slurry was equally distributed among the two pair motors.

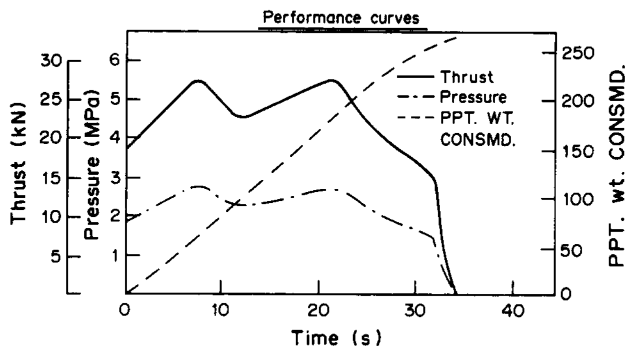




Design parameter		
Outside diameter	m	0.815
Propellent weight	t	1.06
Motor mass ratio	–	0.875
Design MEOP	MPa	4.41
Action time VAC. Isp	Ns/kg	2717
Action time	s	45
Maximum thrust in VAC.	kN	90.7

Fig. 5. Stage 3 motor.





Design parameters

Outside diameter	m	0.657
Propellant weight	t	0.262
Motor mass ratio	-	0.847
Design MEOP	MPa	2.94
Action time VAC. Isp.	Ns/kg	2776
Action time	s	33
Max. thrust in VAC.	kN	26.83

Fig. 6. Stage 4 motor.

The ground tests and a flight test have confirmed close correspondence of the strap-on-motor performance as shown in Table 2.

5.2. *Improvements in the propellant system*

The propellant system of the first and second stage was improved to provide higher energetics, by improving the solids loading. While retaining the same grain configuration, the aluminium content in the propellant was changed from 12 to 18%. This yielded an improvement in the propellant specific gravity of 0.07 and specific impulse by 59 Ns/kg. Marginal adjustments in the nozzle dimensions were incorporated to maintain the MEOP within limits.

During development of the above motors technical problems were encountered chiefly on account of the higher aluminium loading in the propellant. One of the problems was the poorer strain capability exibited by the propellant, as a result of which the motors developed cracks on the port surface of the grain. After some detailed study the problem was overcome by the introduction of larger areas in stress release flap and by adopting lower cure temperature for the propellant.

Table 2. Performance of strap-on motors

	Ground test		Flight test			
			D1		D2	
	ASO-02	ASO-03	ASO-01	ASO-02	ASO-01	ASO-02
Ignition delay (s)	0.195	0.160	0.23	0.218	0.160	0.176
Ignition peak at (s)	0.360	0.369	0.45	0.45	0.392	0.392
Motor peak at (s)	45.3	44.7	43.5	53.5	43.33	43.25
Burning time (s)	45.64	45.2	44.0	44.0	44.14	43.92
Action time (s)	51.04	50.28	49.95	49.95	48.97	48.43
Igniter peak (MPa)	7.31	7.31	6.78	6.78	7.45	7.33
Motor peak (MPa)	4.05	4.11	4.04	4.07	4.25	4.25
Ignition peak (MPa)	2.9	2.84	2.92	2.91	2.9	2.94
Action time av. pr. (MPa)	3.06	3.1	3.04	3.05	3.15	3.15
Burn time av. pr. (MPa)	3.14	3.19	3.14	3.16	3.26	3.25
Pdt. integral (burn time) (MPa-s)	143.52	144.01	138.15	138.81	143.71	142.54
Pdt. integral (action time) (MPa-s)	156.47	156.27	151.66	152.35	154.21	152.74
Propellant weight (kg)	8536	8518	8613	8637	8622	8631
Vac. thrust average (from pr. data) (kN)	432.5	438.5	428.4	430.4	444.8	444.1
Thrust max. vac. (from pr. data) (kN)	560.2	573.5	570.6	574.7	589.2	589.5
I_{sp} vac. (Ns/kg)	2477	2513	2469	2471	2488	2464

Table 3. Performance improvements

	First stage	Second stage
Outside diameter (m)	1.0	0.8
Propellant weight (t)	8.9	3.2
Motor mass ratio	0.853	0.845
Design MEOP (MPa)	4.41	4.41
Action time vac. I_{sp} (Ns/kg)	2541	2707
Action time (s)	45	36
Maximum thrust in vac. (kN)	702	304

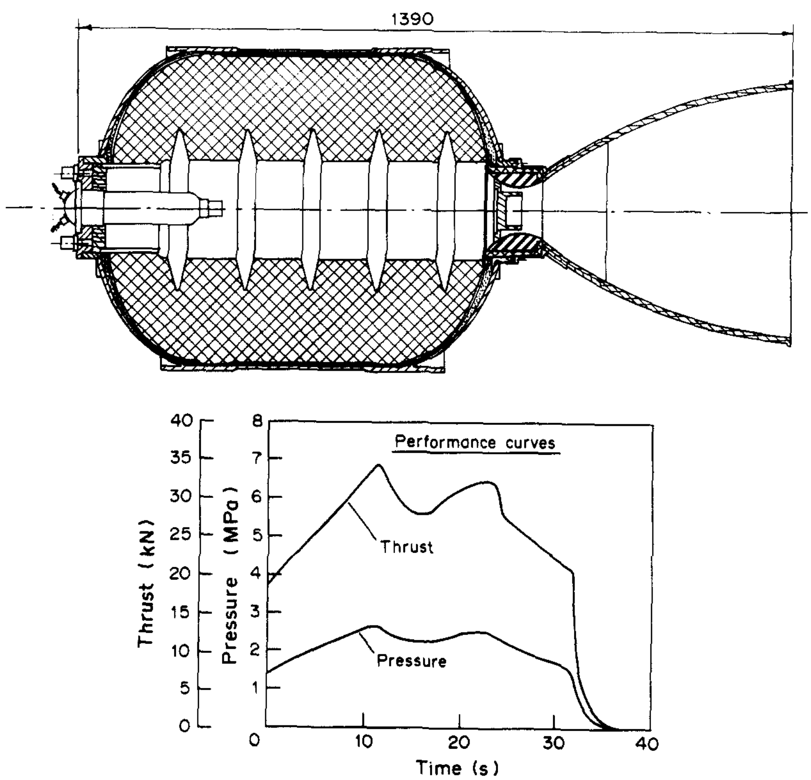
Problems of heavy erosion in the nozzle convergent was also encountered. This problem could also be addressed as due to the impingement of the aluminium particles. The problem was overcome by compensating additional liner sacrifice by higher thickness carbon phenolic ablative materials.

5.3. Improvements in the apogee motor

In this case, the main effort was towards reducing the inert weights and not towards increasing the propellant energetics. This was achieved by re-designing the motor case with Kevlar 49 aramid fibre in place of E glass. The motor case length was also slightly increased to accommodate an additional 45 kg of propellant. The nozzle geometry was contoured to obtain the required expansion ratio in a shorter length and the chamber insulation thickness were also optimized. The motor was taken through the cycle of qualification tests, including the specified environmental levels. Figure 7 shows the major particulars of the apogee motor. The apogee motor was flight proven in the last flight of the SLV.

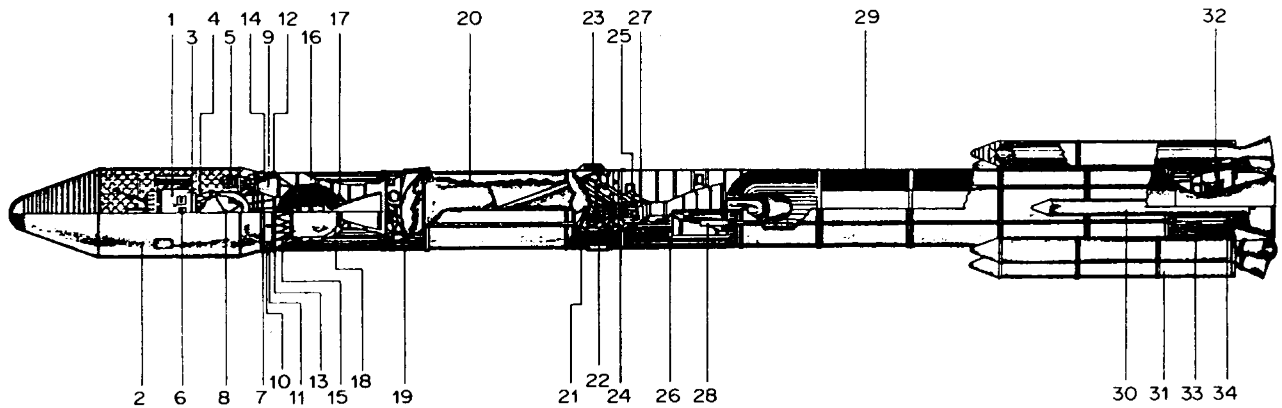
6. DEVELOPMENT OF LARGE MOTORS

The polar satellite launch vehicle under development will have the capability of placing a 1000 kg payload in a 900 km sun-synchronous orbit. The vehicle consists of four main propulsive stages with six strap-on motors for thrust augmentation. The vehicle is approx. 45 m tall with a diameter of 2.8 m



Design parameter		
Outside diameter	m	0.655
Propellant weight	t	0.317
Motor mass ratio		0.905
Design MEOP	MPa	2.943
Action time VAC. Isp	Ns/kg	2756
Action time	s	33.4
Max thrust in VAC.	kN	35

Fig. 7. Apogee motor.



1. Payload
2. Heatshield
3. Payload separation plane
4. Payload adaptor
5. Equipment bay
6. Heat shield separation plane vertical
7. Heat shield separation plane horizontal
8. Fourth stage propellant tank
9. Fourth stage engine (2)
10. Antennae
11. Reaction control thruster
12. Third stage separation plane
13. Second stage separation plane
14. Interstage 3/4
15. Third stage adaptor
16. Third stage motor
17. Flex nozzle control system
18. Interstage 2/3U
19. Interstage 2/3L
20. Second stage propellent tank
21. Interstage 1/2U
22. Retro rocket (4)
23. Ullage rocket (4)
24. First stage separation plane
25. Gimbal control system
26. Interstage 1/2L
27. Second stage engine
28. Retro rocket (8)
29. First stage motor
30. SITVC injectant tank (2)
31. Strap-on motor (6)
32. SITVC system (24)
33. Base shroud
34. Roll control engine (2)

Fig. 8. Polar satellite launch vehicle.

at the first stage booster and a diameter of 3.2 m at the heatshield. The vehicle weighs 275 tonnes at lift off. The major subsystems of the vehicle are shown in Fig. 8.

As can be seen, besides the strap-on the vehicle is powered by two solid stages, i.e. the first and third stages. The strap-on motors are derived from the augmented satellite launch vehicle described under section 5.1.

In the development of these motors many new technologies have been developed and are described below:

6.1. PS-1 booster

This booster provides the main lift off thrust to the vehicle and along with the aid of the strap-ons lifts the vehicle to an altitude of 57 km, imparting to it a velocity of 2 km/s. The motor contains 125 tonnes of HTPB propellant providing a take off thrust of 360 tonnes. The stage nozzle is equipped with a secondary injection thrust vector system for providing control in the pitch and yaw directions. Roll control is separately provided by RCS thrusters.

The booster is constructed in five segements each of nominal diameter of 2.8 m and height of 3.4 m. Each segment is a separately insulated cast with propellant and assembled and held together at the tongue and groove joint by means of 144 pins. The central segments are interchangeable as they employ the same grain geometry. The rocket exhaust gases are led out through a conventional convergent–divergent nozzle with carbon and silica thermal protection systems. Ignition is achieved by means of pyrogen igniter located at the head end of the motor.

6.1.1. Motor case. For the design of the motor case the choice of material was carried out based on (a) high specific strength and stiffness, (b) better fracture properties, (c) easy fabricability and weldability, (d) relative cost, (e) simple heat treatment, (f) effective and easy quality control and (g) availability. After survey of various materials the choice was narrowed down to three steels, 15 CDV 6, maraging steel 250 grade and D6 AC. The preliminary design and comparative performance factors were studied as shown in Table 4. It was noted that while D6 AC may offer lower cost, its poor weldability and the infrastructure required for adopting weld free construction were both time consuming and costly. Use of 15 CDV 6 tends to make the motor case heavier with resultant loss in payload. Except for cost, maraging steel satisfied all the criteria listed above. However, in terms of the overall material, fabrication and heat treatment and facility cost, the overall cost margin was not too high. Consequently the choice was finalized with maraging steel 250 grade.

The fabrication process involved sheet rolling and welding to form stub cylinders, separate machining of the forging, assembly welding of the forgings and stub cylinders, ageing treatment and final machining and drilling. The major technology development areas were (a) developing efficient welds, (b) ultrasonic inspection of the welds for detecting tight cracks and (c) use of rounding fixtures and drill jigs to obtain segment rigorous inspection and non destructive evaluation. Final acceptance of the segments was based on proof pressure testing each segment to a pressure of 6.47 MPa. During pressure testing extensive strain gauging, dilation measurements and monitoring for crack growth through acoustic emission were incorporated. Figure 9 shows the general fabrication process adopted. The motor segment joint is of tongue and groove variety incorporating capture feature. The pressure sealing of the case is achieved by means of two "O" rings, one of which is in the compression mode. The segment joints are held together by means of 144 pins also made of maraging steel. The motor case is provided with skirt extensions at the forward and aft end for mating with the upper stage inter-skirt and the base shroud assemblies respectively. The igniter hardware and nozzle hardware are attached to the case by threaded fasteners. To ensure no fracture-related problems are encountered, elaborate laboratory level studies were undertaken. These studies included processing of deliberately flawed specimen, studies on the ultrasonic detection methods, sensitivity to the ageing parameters, subscale manufacture of pressure vessel with introduction of flawed panels and studying of their behaviour and introduction of acoustic emission sensing techniques during motor pressurization. All these studies have held in the

Table 4. Motor case materials

	15 CDV 6	D6 AC	M250
Strength UTS (MN/m^2)	997	1344	1765
YS (MN/m^2)	907.2	1240.9	1725
Toughness KIC ($MN/m^{-3/2}$)	142	100	100
Cost	High	Less	High
Reliability	High	Good	Good
Heat treatment	Quenched and tempered close control required	Quenched and tempered complex close control required	Solution annealing and ageing. Simple and fairly wider tolerance on control parameters
Fabrication	Roll and weld	Shear spin weld free	Roll and weld
Applications	SLV motors	Titan, Shuttle, Minutman	156 and 260 in. diamotors PS-1 motor

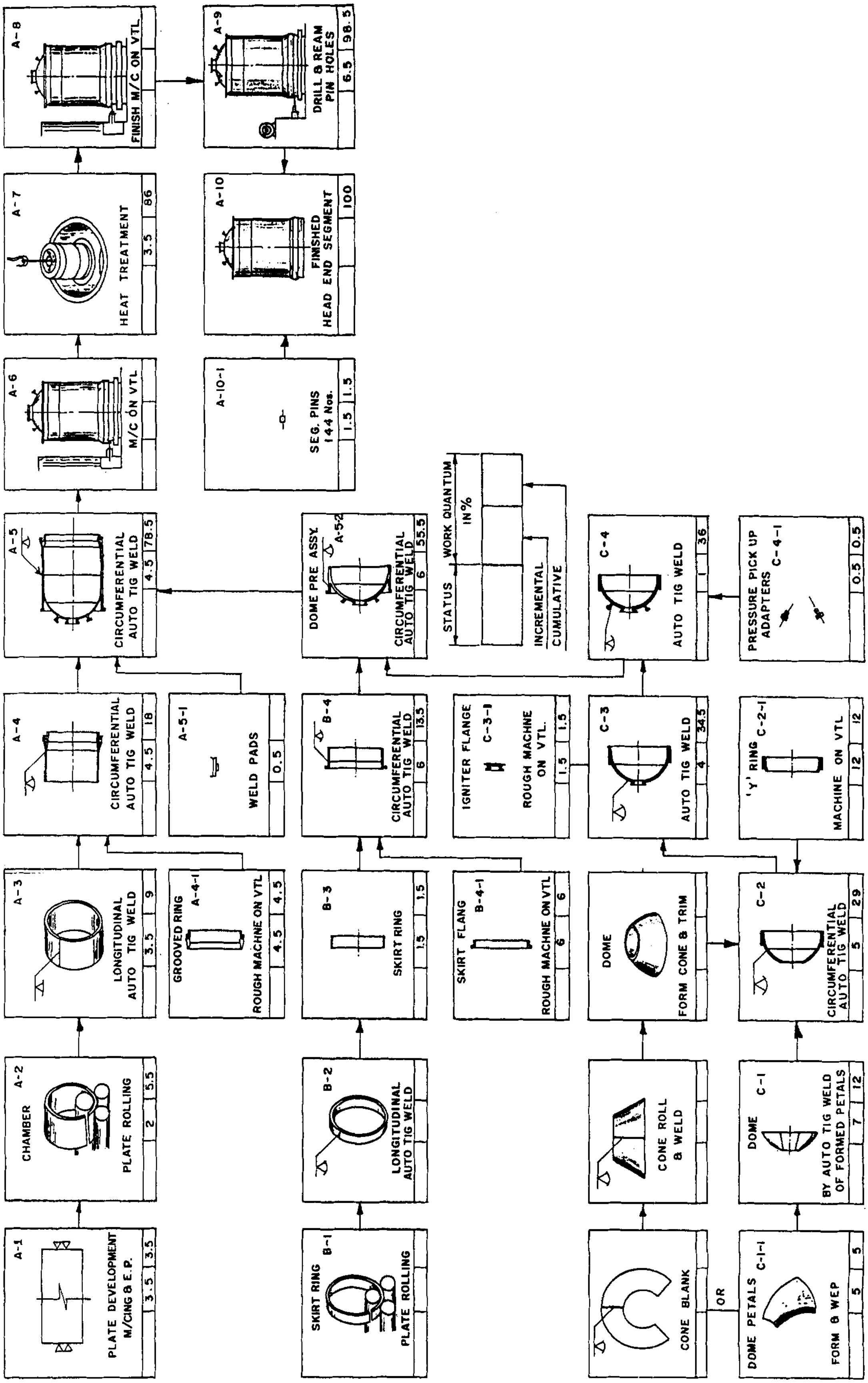


Fig. 9. Fabrication process of PS-1 motor case.

Table 5. Propellant properties of first stage PSLV

% Elongation	35 (min)
Initial modulus (MPa)	2.45 to 3.9
Equilibrium modulus (MPa)	1.9 (nominal)
Specific gravity	1.77 (min)
Hardness shore A	70 ± 5
Dewelting strain (%)	12 (min)
Burn rate of main motor at 3.92 MPa (mm/s)	8.3 ± 0.2

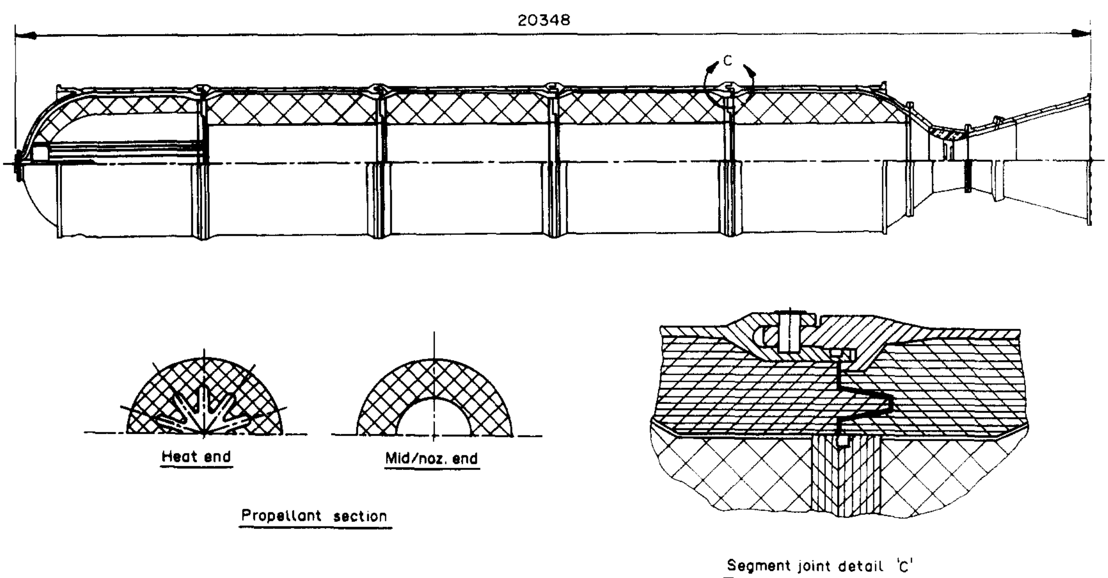
successful realization and acceptance testing of the motor segments.

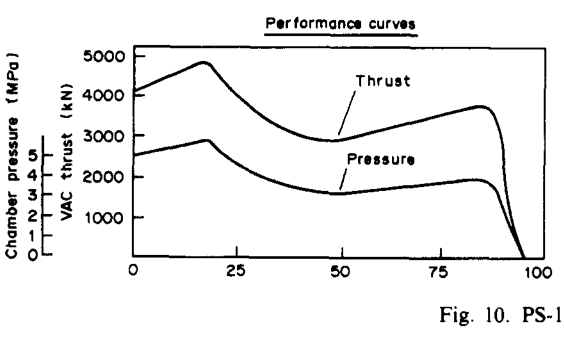
6.1.2. Propellant system. Propellant is cast into each segment separately. The head end of the grain has a deep fin configuration, essentially designed to provide high initial burning surface to obtain the required take off thrust. The entire propellant weight of 22 tonnes used in the segment is consumed in the initial 20 s. The remaining segments all have tubular grain configuration of average bore of 1200 mm and containing approx. 25–28 tonnes of propellant.

The propellant itself is a 86% solids loaded HTPB based system formulation tailored to give a burn rate of 8 mm/s at the motor operating average pressure. The achieved propellant properties are indicated in Table 5.

The chamber is insulated from the propellant hot gases by a nitrile rubber insulation of the same type as employed for the smaller motors described earlier. The insulation procured in unvulcanized sheets is laid into cleaned and prepared motor chamber, built to the required thickness and cured in an autoclave. The end faces of the insulation are machined to provide a reverse tongue and groove configuration. The ends of the grain are inhibited and made to butt against each other during assembly. The space between the machined insulation faces is filled with a silicone potting compound and this along with the butting inhibited faces ensures a long gas path to prevent leakage and undesirable consequences. The interface between the insulation and the propellant is coated with a cured liner system based on HTPB binder. The details of the motor and its performance are shown in Fig. 10.

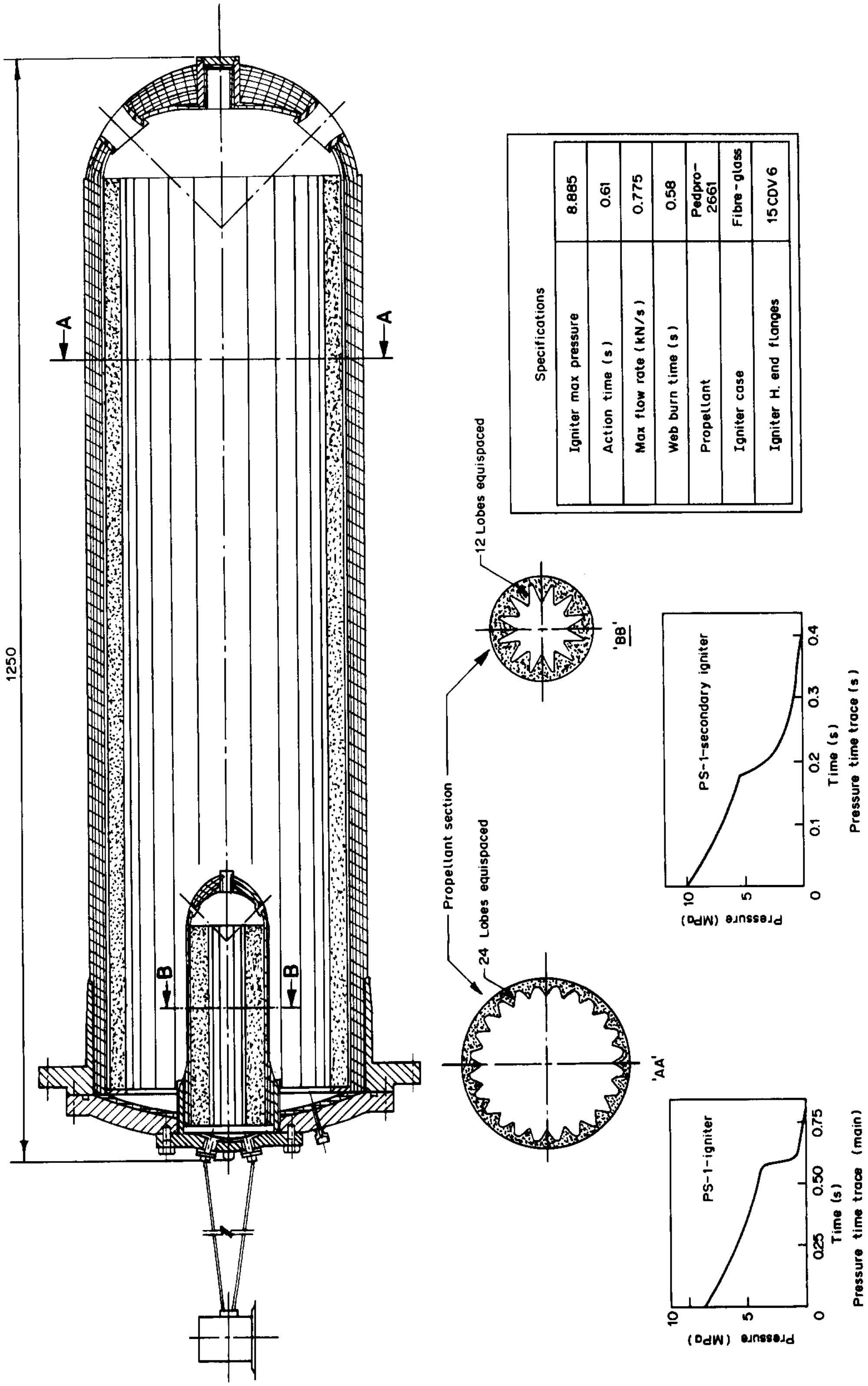
6.1.3. Nozzle. The motor nozzle is of external type. The structural back up chamber is made of 15 CDV 6 with provision for mounting the SITVC valves. The throat insert is made from carbon phenolic material wound at 60° to the motor axis and cured at high pressure in the hydroclave. Sub-scale tests have been carried out and erosion rate of 0.2 mm/s of the CP





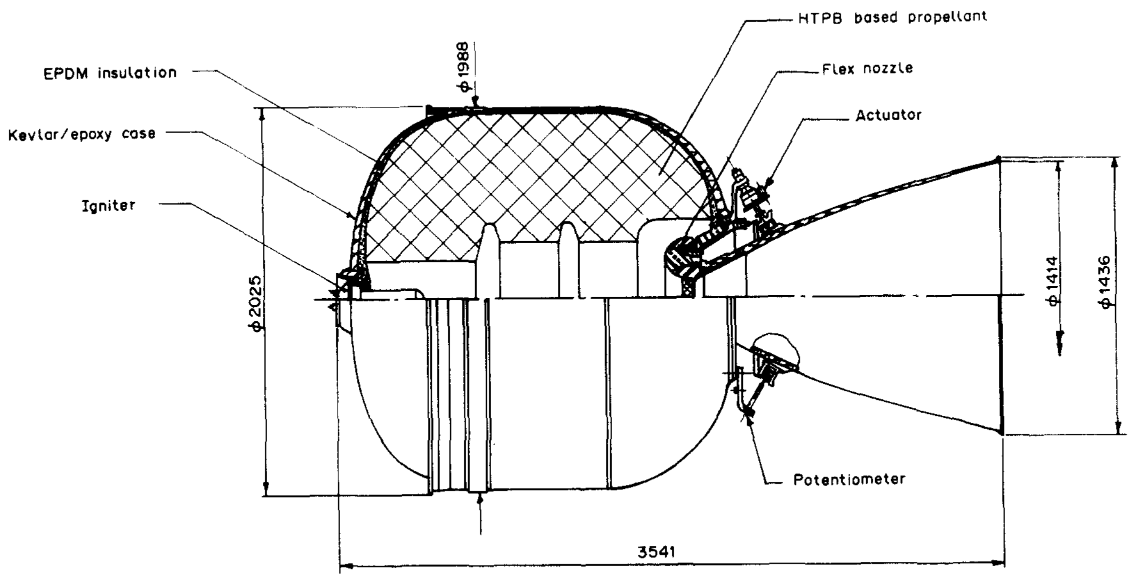
Performance		
Outside diameter	m	2.804
Propellant weight	t	127
Motor mass ratio (min)		0.873
Design MEOP	MPa	5.88
Action time VAC. Isp. (min)	Ns/kg (s)	2570 262
Action time	(s)	94.25
Max. thrust in vacuum	kN	4860

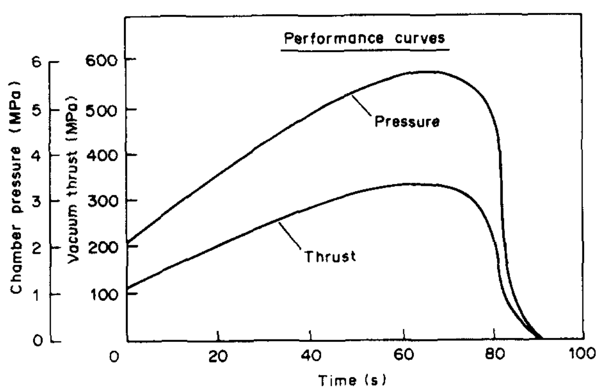
Fig. 10. PS-1 booster.



Specifications	
Igniter max pressure	8.885
Action time (s)	0.61
Max flow rate (kN/s)	0.775
Web burn time (s)	0.58
Propellant	Pedpro-2661
Igniter case	Fibre-glass
Igniter H. end flanges	15CDV6

Fig. 11. PS-1 igniter.





Design parameter		
Outside diameter	m	1.988
Propellant weight	t	7.297
Motor mass ratio	–	0.915
Design MEOP	MPa	6.37
Action time VAC. Isp	Ns/kg	2857.7
Action time	s	85.75
Max. thrust in VAC.	kN	328.7

Fig. 12. PS-3 motor.

has been recorded. The thermal protection system for the convergent is constructed with rosetted carbon phenolic and cured in hydroclave. The divergent cone consists of tape wound carbon phenolic down stream of the throat insert and extending slightly beyond the SITVC zone followed by tape wound silica phenolic in the regions of down stream of the SITVC zone. Again based on the observation in the subscale test of the erosion due to the SITVC and main flow interaction additional liner thickness has been built in the SITVC region.

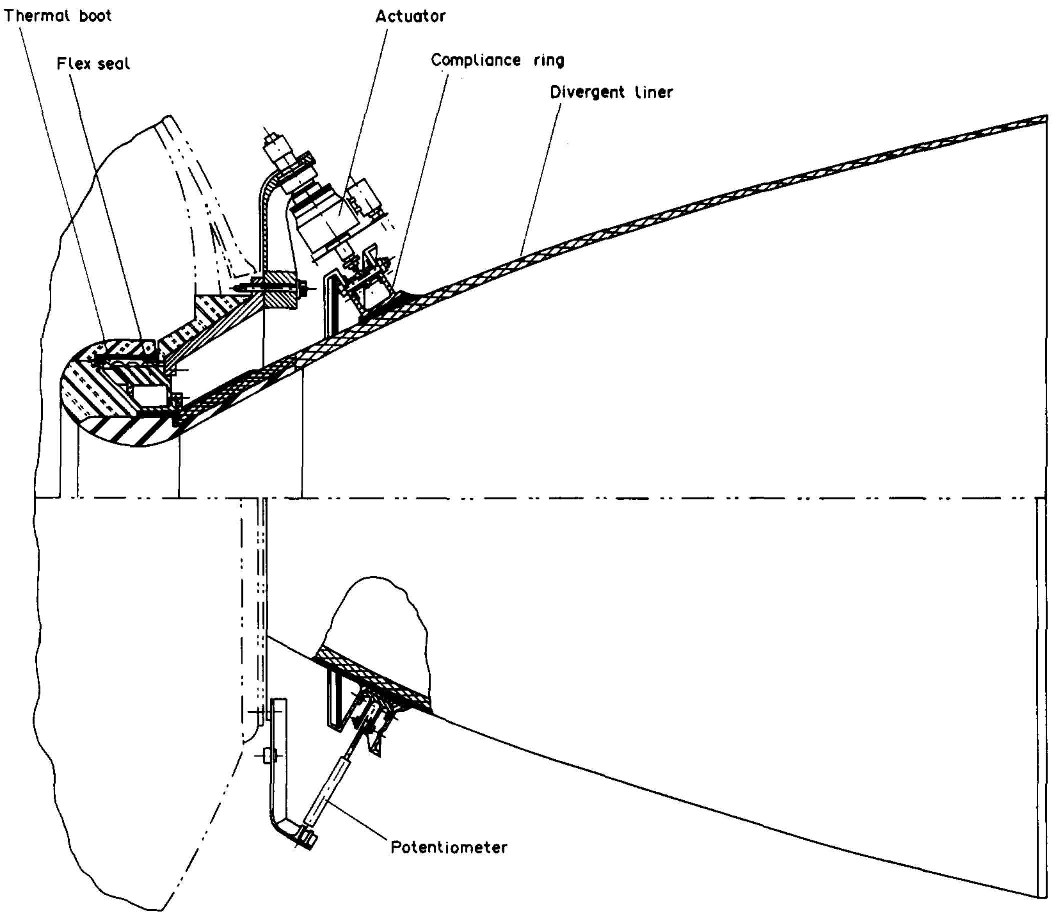
6.1.4. Igniter. A pyrogen igniter of approx. 300 mm dia and providing high mass flow is employed for igniting the motor. The igniter employes an HTPB composition and uses a fibreglass case. The operation time of the igniter is approx. 1 s. A smaller pyrogen igniter employing a 2 kg charge is used to initiate the main igniter. The igniter details are provided in Fig. 11.

7. PS-3 MOTOR

This is a high performance motor designed to achieve a propellant fraction of 0.915. The motor has a dia 2 m and is equipped with flex bearing system for thrust vector control. The motor design provides an option for off-loading the propellant. New developmental ground in the areas of motor case design and manufacture, and flex seal thrust vector control system have been broken. The major features of the motor are shown in Fig. 12 and described below:

7.1. Motor case

The motor case material was selected to be kevlar after a comparative study of other potential case material like titanium, fibreglass etc. The case is of kevlar/epoxy filament wound construction for the shell and carbon/kevlar/epoxy hybrid lay up construction for the skirt extension at the head end. The



Design features

Type : submerged, contoured – with flex seal

Throat diameter	: (mm)	195.4
Exit diameter	: (mm)	1414
Expansion ratio	: —	52.3
Total length	: (mm)	1802
Initial angle	: (deg)	27
Exit angle	: (deg)	15
Nozzle weight	: (kg)	280
Vectoring capability	: (deg)	±3

Fig. 13. PS-3 flex nozzle.

skirt is used as a structural link between the shell and vehicle structure/thrust frame and also it is used for handling during the mtor processing. Aluminium alloy forgings are used for end opening fitting and for skirt fitting. The case is designed for a maximum pressure (MEOP) of 6.37 MPa, with minimum burst pressure of 5.05 MPa. The factor of safety used of the design is 1.25. The motor case is designed for performance factor of 30×10^3 m. The motor case is qualified structurally before subjecting to hot tests. The case design and performance parameters are summarized in Table 6.

7.2. Propellant system

The basic propellant composition is the same as used for the first stage except that the burn rate is derated by adjustments in the burn rate modifier content. However, with the larger area ratio of 52 being employed for the nozzle a vacuum I_{sp} of 2855 Ns/kg is being targetted. The propellant grain port is of slotted configuration to maximize the propellant loading. The grain geometry is derived by initially casting with a cylindrical mandrel and subsequently machining to the required configuration. The grain also offers off-load capabilities. The insulation system employed is based on EPDM with cork filler to render it light weight. A specific gravity of less than one is achieved with this insulation system. Both moulded insulation and autoclave cured insulation routes have been developed for use.

Table 6. Salient design features of motor case

Configuration	Unequal opening polar and hoop wound single skirt extension at head end L/D × 1.05
Overall length (mm)	2083.5
Max. dia at skirt (mm)	2025
Opening diameter (mm)	
Head end	200
Nozzle end	750
MEOP (MPa)	6.4
Safety factor	1.25
Total weight (kg)	340
Performance factor (PV/W)	29.8×10^3 m
Materials used	
Kevlar/epoxy	Polar and hoop winding of shell
Kevlar cloth/epoxy	Doilies
Kevlar/carbon/epoxy (hybrid)	Skirt extension
Aluminium alloy (7075.77352)	End boss and skirt ring

7.3. Nozzle

The nozzle is designed with 20% submergence and with an expansion ratio of 52 to satisfy the overall length and performance requirements. Graphite is used as throat insert whereas the rest of the thermal protection system comprises carbon and silica phenolic composites. A fibreglass wrap up over the divergent cone provides structural stiffness. A compliance ring is attached to the nozzle divergent cone to provide atachement to the TVC actuator system.

Table 7. Salient design features of PS-3 nozzle

Configuration	Submerged contoured nozzle with flex bearing
Throat diameter (mm)	194.4
Area ratio	52.3
Total length (mm)	180.2
Nozzle weight (kg)	280
Vectoring capacity	±3 (omni-axial)
Submergency (%)	19.6
Flex bearing	
Configuration	
Overall	Cylindrical
Shim	Conical (45°)
Moment arm (mm)	750
Inter joint angle	41.34
Outer joint angle	48.65
Pivot radius	332.34
Thickness of elastomer (mm)	3 mm
Thickness of shim (mm)	(4.5/5.5/5.5)
Torque/degree (kN.m)	2
Actuator capacity (kN)	11.8

The flex bearing is designed with a forward pivot point from considerations of actuation force and envelop requirements. Conical bearing configuration is chosen as the omni-axial deflection required is only 2° (3° as qualification level). The elastomer, based on natural rubber of nominal thickness 3 mm is adhesively bonded with steel reinforcements of 4.5 mm thick. Each seal is made up of 6 reinforcements and 7 elastomer pads. The seal located behind the throat housing is driven by two electro-mechanical actuators located 90° apart. A thermal boot protects the bearing from over heating. The main details of the nozzle and flex bearing are summarized in Table 7. A schematic of the nozzle assembly can be seen in Fig. 13.

8. SPECIAL PURPOSE MOTORS

Besides the stage motors described above, the polar satellite launch vehicle employs solid motors for achieving separation between the stages and also for providing ullage volume acceleration to the liquid second stage. These motors are all of nominal 200 mm dia and employ propellant in the weight range of 14–38.5 kg. The motors used for the retro purposes have low burning time whereas the ullage motor is designed for a burn time of 5.5 s. All the motors have canted nozzles to ensure that the exhausts from the motors do not affect the main vehicle structure. Details of these motors are shown in Table 8.

9. CONCLUSION

Solid motors—both operational and those under development—for ISRO's sounding rockets and launch vehicle programmes have been briefly described in the above paragraphs. For the development of the motor subsystems, the requirement of necessary design tools and design software have also been catered to. The basic infrastructure for raw materials and fabrication available with the Indian industry has been fully utilized. However, propellant processing facilities and composite products processing facilities along with non destructive evaluation capabilities have been established within ISRO. Assembly and testing requirements comprising environmental facilities, single and six component

Table 8. Feature of special purpose motors

Parameters	Retro-1	Retro-2	Ullage-2
Motor dia (mm)	209	209	207
Motor length (mm)	1414	835	1271
Burn time (s)	1.3	1.6	5.5
Maximum pressure (MPa)	14.7	14.7	4.4
Average thrust (kN)	48.5	22.6	15.3
Propellant weight (kg)	26.8	13.9	38.5
Nozzle cant angle (°)	6.75	29	8
Nozzle area ratio	21	13.2	18
Application	Separation of spent stage 1	Separation of spent stage 2	Acceleration of vehicle prior to liquid stage ignition

test stands and altitude test facilities have also been established in house.

The basic aim of self sufficiency in the realization of solid motors has been achieved by the indigenous development and production of raw materials and crucial technologies. Besides engineering of the process for propellant, composite motor cases and nozzles, facilities for manufacturing and inspection of these have been set up. In addition many technologies developed within ISRO have been transferred to industry. Chief among these are the production of HTPB binder, phenolic resin and high silica cloth. Capacities for ammonium perchlorate are available in ISRO and in Indian industry. Indian industry has capabilities to meet the requirements of aluminium powder, adhesives, insulation products and large scale fabrication of motor cases.

With all the above capabilities, the solid motor programmes of ISRO are poised for a continued and stimulated growth.